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APPLICATION TO THE BOLIDE OF 11/17/1998**

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LARGE LEONID ENTRY MODELING: APPLICATION TO THE BOLIDE OF 11/17/1998

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ABSTRACT

In this paper we apply the theoretical entry model of ReVelle (2001c) to the large Leonid bolide of November 17, 1998. We modeled the entry both using hypersonic aerodynamics and compared the results to the infrasonic detection and interpretation of the event by ReVelle and Whitaker (1999).

1. INTRODUCTION AND OVERVIEW:

1.1 Low frequency acoustics and infrasonics and bolides as an infrasonic source

This section is a very brief overview of the field and characteristics of low frequency, sub-audible acoustics (~ 0.01 to 10.0 Hz), i.e., the field of infrasonics, in analogy to the infrared light regime for electromagnetic wave propagation. Further references and details are provided in ReVelle (1997). It is well known that explosive sources with progressively larger energies produce correspondingly lower frequency (longer period) signals at maximum amplitude. Such long-distance propagation can occur with very small dissipation effects: The propagation for larger sources or during inversion type conditions in the planetary boundary layer can also be influenced by the fundamental mode, i.e., the Lamb wave which propagates along the Earth's surface as an evanescent wave. Atmospheric propagation is also characterized by various forms of ducting including a tropospheric duct (Polar jet stream-associated and due to wind perturbations), a stratospheric duct (with-wind and against-wind along with effects due to wind perturbations) and finally a thermospheric duct. The refractive propagation is controlled by changes with height and range of the local adiabatic, thermodynamic sound speed

(due to the combined effects of air temperature and mean molecular weight) and of the horizontal winds. It is also due to the perturbations from ambient turbulence and from naturally occurring acoustic-gravity waves from a multitude of sources. The analyses of the wave propagation in the near-field can be done using ray theory type approaches, but for sufficiently great ranges, a normal mode (full-wave) type synthesis is needed, i.e. for $R > 2H^2/\lambda$ (H = duct height, λ = wavelength). For example, at a frequency of 0.1 Hz signal for the stratospheric duct, $R > \sim 1430$ km, which is the range beyond which geometrical acoustics ray tracing should be abandoned in favor of a full-wave approach.

Finally, waves are detected using multi-element arrays (using standard cross-correlation beam-forming) in order to determine the back-azimuth and elevation arrival angle (trace velocity of arrivals) of the assumed planar wavefronts.

1.2 Bolide aerodynamic characteristics

The entry of a sufficiently large Leonid bolide can be categorized as having a large Reynolds number (turbulent flow interaction), a large Mach number (hypersonic, compressible flow and strong shock waves and atmospheric as well as ablative products radiation) as well as a small Knudsen number, Kn (continuum flow regime). Thus, such meteoroids are expected to experience severe ablation and fragmentation effects (depending on their tensile and compressive strength) since the ablation interaction number is also large (ReVelle, 1979). For more details see Cepelch et al. (1998) and ReVelle (2001c).

1.3 Line sources and modified line sources:

For small, Kn , the line source blast wave relaxation radius, R_0 , \sim Mach number \cdot diameter ≥ 10 m for ground based detection (ReVelle, 1976). Thus, the wavelength, $\lambda \sim 2 \cdot 81 \cdot R_0$ and the frequency, f , of the wave sources at $10 \cdot R_0$, is $= c_s / \lambda$, where c_s is the local adiabatic thermodynamic sound speed. As the downward heading wave normals propagate a transition from weak shock propagation to linear acoustic propagation generally occurs at sufficient range (ReVelle, 1976, 1997). The wave normal paths are subject to refractive effects from the changes in the vertical and horizontal profiles of the time variable atmospheric temperature and winds (Snell's law of acoustics)

The waves are also subject to scattering and diffraction effects due to the presence of acoustic-gravity waves and turbulence aloft.

2. OBSERVATIONS OF THE NOVEMBER 17, 1998 LEONID BOLIDE:

2.1 Basic Infrasonic observations

$\Delta t = \{z_{\text{end}} / \cos(90-A)\} / \langle V_{\text{ph}} \rangle$ for a straight, unrefracted path

The time delay, Δt , is between the visual sighting or instrumental recording of the bolide and the arrival of the infrasonic signal. This was assumed to be a direct, non-ducted path from the source to the observer. In the above z_{end} is the end height and $\langle V_{\text{ph}} \rangle$ is the height averaged phase speed, which includes the height averaged effects of sound speed and of the horizontal winds in the direction of travel of the wave. The angle A is the elevation arrival angle of the infrasound at the ground array. We now analyze the possibilities for $\langle V_{\text{ph}} \rangle = 0.309$ km/s ($\langle T \rangle = 238.5$ K) and $A = 68.3^\circ$. If signals were propagating against a uniform 30 m/s wind at all heights for this source height, we find that $\Delta t = 347.2$ s = 5.78 minutes for $z_{\text{end}} = 90$ km (with a $\langle V_{\text{ph}} \rangle = 0.279$ km/s). The observed time delay: ~ 5 minutes, 49 seconds (= 5.82 minutes) indicates a discrepancy of ~ -0.58 % (theory earlier than observed) If we assume instead that $z_{\text{end}} = 85$ km, $\Delta t = 327.9$ s = 5.46 minutes, which is about -6.1 % early. Both of these are clearly very acceptable time delays. The total distance to the bolide can range from 89.0-102.2 km for infrasonic source heights from 85-95 km.

2.2 Additional Infrasonic Observations

A brief summary of additional relevant infrasound parameters for this bolide is given in Table 1. below.

Table 1. Infrasound from the 11/17/1998 Leonid bolide (ReVelle and Whitaker, 1999)

Deduced Parameters	IMS Prototype Array in Los Alamos, New Mexico
Arrival time of infrasonic signals	10:10:49 UTC
Total signal duration	~ 4 seconds (for the strongest signals)
Bolide source azimuth	353.6 \pm 0.4 deg
Bolide source altitude	93.5 km
Total range to the bolide	97.9 km
Slant range signal velocity	0.27 km/s
Signal trace velocity	920 m/s
Signal elevation arrival angle	68.3 deg
Signal type	Direct path: Source to observer
Dominant frequency content at maximum signal amplitude	0.71 Hz: (1.4 seconds)
Maximum, cross-correlation coefficient (squared value)	0.92
Maximum signal/noise ratio	4
Maximum signal amplitude	2.1 microbars (0.21 Pa)

2.3 Ancillary observations

Ancillary observations have come from at least two ground-based video patrol camera detection's near Albuquerque as well as radiometer data at SNL (R.E. Spalding, Sandia National Laboratory, personal communication, 1998). Their corrected estimate of the bolides apparent stellar magnitude from radiometers is -14 (normalized to 100 km and corrected for range. The original uncorrected magnitude estimate is -12). In addition there were numerous visual reports and photographic records from this event as well. In Los Alamos there were sightings by Dr. T. Kunkle, EES-5 and Dr. S. Becker, X-TA, both of Los Alamos National Laboratory. They both independently witnessed the bolide and its persistent train, which could be visually followed for many minutes after the event. Their estimates of the bolide observations produced an estimate of -10 stellar magnitudes. Their independent time for the sighting was at 10:05 UTC at an estimated source location of 106.40 W, 36.05 N.

There was also ground-based, intensified all-sky camera coverage from Placitas, NM, 65 km to the south of Los Alamos by Dr. W.T. Armstrong, EES-8 of the Los Alamos National Laboratory. Using the data at Placitas and from the visual observations in Los Alamos an estimated height of the bolide from the two intersecting bearings yielded 91 ± 7 km ($\sim 84 - 98$ km). There were also independent observations taken at the USAF Starfire Optical Range. These yielded a horizontal entry angle of 42 degrees, a bolide heading of 302 degrees (from SE-NW) and an end height of 85 km. With the latitude and longitude of our IMS (International Monitoring System) infrasound array, Drummond independently calculated the azimuth and elevation angle of the arrival of the infrasound in Los Alamos from the Starfire data (personal communication, 2001). The results are virtually identical for each of these infrasonic parameters, which leaves absolutely no doubt about the reality of this infrasound detection even though it is from a type IIIA. or IIIB. body at an altitude of the mesopause. As shown below, the main reasons for our success infrasonically was the low wind-noise at the time of the event in combination with the very large and unusual initial size of this Leonid.

3. ENTRY MODELING OF LARGE LEONID BOLIDES

In a companion paper (ReVelle, 2001c), we have used simple ablation theory for either the case of constant sigma or of a height variable sigma over small altitude intervals to model this Leonid bolide. The constant sigma solutions were done assuming source properties for bolide group IIIA. or for meteor group B. The height variable sigma values were determined directly from theory allowing for both convective and radiative heat transfer, etc. For either constant shape or allowing for shape change, we used the μ parameter over the respective ranges: $\mu = 2/3$, $0 \leq \mu < 2/3$ and $\mu < 0$. We also assumed either a uniform or a porous meteoroid model. This approach allowed us to calculate the expected entry dynamics and luminosity for the 11/17/1998 Leonid bolide over Los Alamos. We have also compared these entry modeling estimates against the observations from SNLA radiometers and from the USAF Starfire Optical Range as well as from observations from the Los Alamos infrasound array as discussed below.

4. MODELING APPLICATION: 11/17/1998 LEONID

The relevant combination of source parameters includes a bolide of either type B or IIIA/IIIB. as listed in Ceplecha et al. (1998) at a known Leonid entry velocity (geocentric) of 70.7 km/s. Recent data taken from the same Leonid storm, but in Mongolia by Spurny produced ablation coefficients intermediate between the statistical values for type IIIA and IIB bolides (Spurny, personal communication, 1999). We initially computed an end height for vertical entry (90 degrees) for a steady state, isothermal or non-isothermal, hydrostatic atmosphere model. Later the elevation of the radiant above the horizon for this Leonid was determined to be 42 degrees as noted above. For this change in entry angle all of the computed end heights move up uniformly about 2.8 km. This change brings the predicted entry dynamics results into even better agreement with the observations. As noted earlier, we tried to model this Leonid using a number of different approximations of the simple ablation theory, using either a single-body model approach or using the catastrophic fragmentation approach in ReVelle (2001d). We initially assumed a spherical shape in all cases. Shape change was initially not considered for a case with constant drag coefficient and ablation coefficient, etc. and μ was set to 2/3 (self-similar ablation and deceleration solution in the single body approximation). We computed the Knudsen number at the end height (= local neutral gas mean free path divided by the radius of the body) We searched for cases with $Kn < 0.10$ (continuum flow). We also computed the maximum stellar magnitude from Naumann and Clifton (1973) for a $\tau_L \sim 0.10$ % (differential luminous efficiency) which is valid for small bodies of chondritic origin while assuming a color index of 0. This should underestimate the brightness of large chondritic (uniform) bodies.

For the hydrostatic, steady state, isothermal atmosphere model, we used a height averaged temperature=238.5 K, pressure scale height = 7.006 km and height averaged sound speed = 0.3096 km/sec, surface pressure= $1.01325 \cdot 10^5$ Pa, surface, neutral gas mean free path= $5.49 \cdot 10^{-8}$ m.

For the bolide, the key parameters assumed were the continuum flow drag coefficient = 0.92, an initial spherical shape factor = 1.208 (ReVelle, 1979). For the extremes of meteor group B to type IIIA or IIIB bolides, we used the following material parameter values.

Meteor Group B:

Bulk density = 1000 kg/m³, $\sigma = 0.08 \text{ sec}^2/\text{km}^2$

Bolide Type IIIA:

Bulk density = 750 kg/m³, $\sigma = 0.10 \text{ sec}^2/\text{km}^2$

For comparison, for type IIIB bolides, the bulk density = 270 kg/m³, $\sigma = 0.21 \text{ sec}^2/\text{km}^2$. Had these values been used in the entry dynamics calculations, we would have had even better agreement than is now predicted regardless of the specific method used. The results of our entry dynamics calculations are as follows (where all magnitude values have standardized to 100 km in the zenith):

Meteor Group B Results:

**$R_\infty = 0.05 \text{ m}$ ($M_\infty = 0.524 \text{ kg}$)
 $E_k = 0.313 \text{ t}$ (TNT equivalent)= source energy
Predicted end heights: 64.1-68.6 km
Knudsen number: $2.1 \cdot 10^{-2}$ to $3.0 \cdot 10^{-2}$
Maximum stellar magnitude: -11.8**

**$R_\infty = 0.1 \text{ m}$ ($M_\infty = 4.19 \text{ kg}$)
 $E_k = 2.5 \text{ t}$ (TNT equivalent)
Predicted end heights: 59.2-63.7 km
Knudsen number: $5.2 \cdot 10^{-3}$ to $7.6 \cdot 10^{-3}$
Maximum stellar magnitude: -14.1**

**$R_\infty = 0.2 \text{ m}$ ($M_\infty = 33.5 \text{ kg}$)
 $E_k = 20.0 \text{ t}$ (TNT equivalent)
Predicted end heights: 54.4-58.9 km
Knudsen number: $1.3 \cdot 10^{-3}$ to $1.9 \cdot 10^{-3}$
Maximum stellar magnitude: -16.4**

Bolide Type IIIA. Results:

**$R_\infty = 0.055 \text{ m}$ ($M_\infty = 0.523 \text{ kg}$)
 $E_k = 0.312 \text{ t}$ (TNT equivalent)
Predicted end heights: 67.0-71.4 km
Knudsen number: $2.9 \cdot 10^{-2}$ to $4.2 \cdot 10^{-2}$
Maximum stellar magnitude: -11.8:**

**$R_\infty = 0.11 \text{ m}$ ($M_\infty = 4.18 \text{ kg}$)
 $E_k = 2.5 \text{ t}$ (TNT equivalent)
Predicted end heights: 62.2-66.5 km
Knudsen number: $7.2 \cdot 10^{-3}$ to $1.05 \cdot 10^{-2}$
Maximum stellar magnitude: -14.1:**

**$R_\infty = 0.22 \text{ m}$ ($M_\infty = 33.5 \text{ kg}$)
 $E_k = 19.98 \text{ t}$ (TNT equivalent)
Predicted end heights: 57.3-61.7 km
Knudsen number: $1.8 \cdot 10^{-3}$ to $2.6 \cdot 10^{-3}$
Maximum stellar magnitude: -16.4**

A series of representative graphs of the results of these calculations are given below in Figures 1. to 4. for the velocity, Knudsen no., ablation coefficient and predicted mass loss, respectively for an initial sphere of radius = 0.10 m.

From our infrasonic analyses (ReVelle and Whitaker, 1999), we have also been able to deduce the source energy of this bolide using our observed infrasonic data totally independently of the entry dynamics modeling effort discussed above. This estimate was made using a line source model of the blast wave generated during entry and the subsequent production of infrasound that was detected at ground level by our prototype array. The model could be used to interpret the energy of this bolide using only the observed wave period at maximum amplitude of the infrasonic signal or in conjunction with the observed wave amplitude. Both approaches give different results, but both are fully consistent with the entry dynamics modeling done here.

Since the entry trajectory of this body is now known quite precisely (personal communication with R.E. Spalding, Sandia National Laboratory), our future plans include a line source ray tracing through an MSIS atmospheric temperature and wind profiles to determine the refractive paths for these unique signals.

5. SUMMARY AND CONCLUSIONS

The first infrasonic detection of a Leonid was made at Los Alamos on 11/18/1998 at ~10:10:49 UT during the Leonid meteor storm. Estimates of source energy are available from hypersonic aerodynamics (ReVelle, 1979, 1993, 1999) with stellar magnitudes having been estimated using a 0.1 % differential luminous efficiency, from SNL ground-based radiometers (R.E. Spalding), from a Los Alamos all-sky CCD camera system (W.T. Armstrong) and from visual observer estimates (T. Kunkle, S. Becker). Finally, we can also estimate the hydrodynamic source energy from independent infrasonic source estimates summarized in Ceplecha et al. (1998). All of the above methods are in reasonably good agreement with a predicted source energy of ~0.31-1.2 t (TNT equivalent). Finally, a cometary origin was definitely confirmed from our analyses of this Leonid, i.e., a very weak fragile material of low density and large ablation coefficient. Regarding the height regimes of the bolide interaction with the atmosphere, we find that the single-body estimates of end height are likely to be too low since fragmentation effects were initially

ignored. Using ReVelle's (1999-2001d) new theoretical approach we have also estimated fragmentation effects as a function of μ for this bolide, which we will report on separately.

6. REFERENCES

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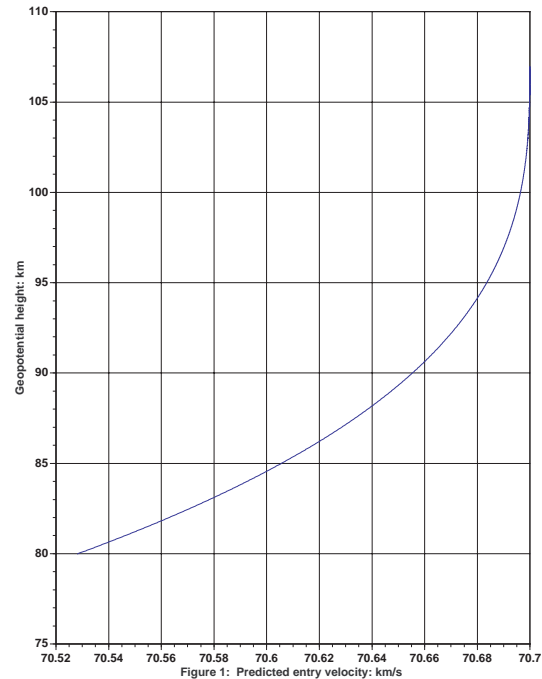


Figure 1. Velocity versus altitude.

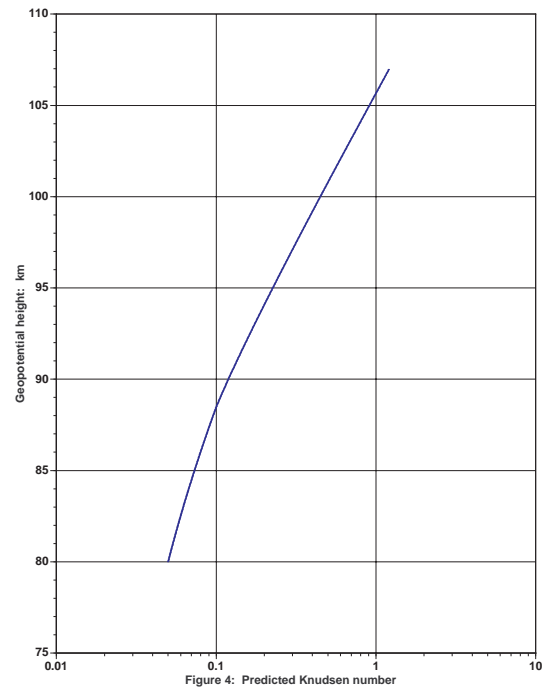


Figure 2. Knudsen number versus altitude.

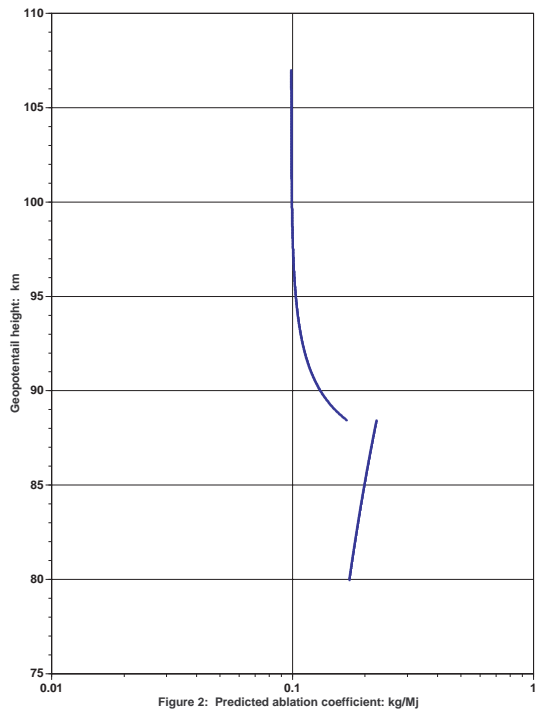


Figure 3. Ablation coefficient versus altitude.

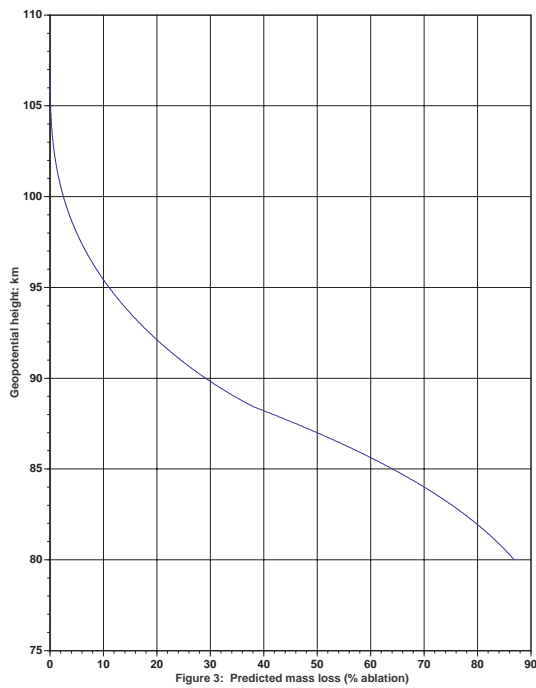


Figure 4. Predicted mass loss versus altitude.